

Digital Processing in Tunneling Spectroscopy

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An alternative approach to detect very weak singularities on the characteristics of a tunnel diode is proposed in which the numerical differential filtering is applied directly to measured current versus voltage dependence instead of the modulation technique commonly used with this purpose. The gains and losses of the both approaches in the particular case of tunneling investigations of semiconductors under pressure are discussed. The corresponding circuitry and mathematical routines are presented.

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INTRODUCTION

One of the modern topics of condensed matter physics is concerned with the studies of the effects of many-particle interactions on electronic transport phenomena.

Many-particle interactions (charge-correlation and/or electron-phonon) may manifest themselves in the tunneling characteristics either due to the variation of the barrier shape or due to the variations of the tunneling probability induced by including additional tunneling channels [1]. E.g., the interaction of the electrons with LO-phonons produces specific singularities in the tunneling spectra of the GaAs-based junctions at biases $\pm 36.5 meV$, corresponding to the energy of LO-phonon in GaAs. Inter-electron interaction in the plasma of a semiconductor is responsible for the appearance of so called Zero Bias Anomaly (ZBA) that looks like a peak of the tunneling resistance at small bias voltages. While magnetoresistive measurements supply the experimental data only for filled subbands of dimensional quantization, the tunneling may provide information for initially empty subbands also. It was shown recently [2], that the tunnel junction Al/ δ -Si-GaAs is a convenient object for investigations of the pressure influence on many-particle effects in the 2D electron system, and the possible metal-insulator type transition was predicted in near-surface δ -doped layer in Al/GaAs(δ -Si) structure under pressure of about 2 GPa.

The observation and the experimental study of this phenomenon implied the necessity of performing tunnel measurements at very large resistivities of the samples aiming to detect very weak singularities on the current-voltage characteristics of a tunnel diode.

In the tunneling spectroscopy a current through the tunnel junction is measured versus the applied bias voltage. The commonly used way of retrieving tunnel spectra is based on performing measurements using a modulation technique. In such a method the sample is fed with a DC bias with an addition of small AC component. The resulting current may be expressed as [3]

$$I(V + a \sin(\omega t)) \approx I(V) + a \left. \frac{dI}{dV} \right|_V \sin(\omega t) - \frac{1}{2} a^2 \left. \frac{d^2 I}{dV^2} \right|_V \sin^2(\omega t) + \dots \quad (1)$$

and corresponding derivatives may be approximated as

$$\left. \frac{dI}{dV} \right|_V \sim \sin(\omega t + \phi_1); \quad \left. \frac{d^2 I}{dV^2} \right|_V \sim \sin(2\omega t + \phi_2). \quad (2)$$

This gives a possibility to reveal very slight singularities, containing a valuable physical information. The straightforward application of a computer to such a measuring procedure is to use the usual modulation technique for analog processing of the signal and then digitize and store the obtained data for future numerical treatment.

This way is the best since it is the simplest one, but this is not the case when dealing with tunnel junctions of very high resistivity. From the experimental point of view the reason for this is that the analog data averaging is performed as a rule with a lock-in amplifier that should be tuned precisely enough to the phase of the signal and should have rather large time constant for better resolution.

The first obstacle is that $I(V)$ characteristic of a semiconductor tunnel junction is highly non-linear so that the phase shift varies during the bias sweep. Next, the active resistance of the bias grows rapidly (by several orders of magnitude) with pressure so that the capacitive constituent of the impedance becomes significant enough to make the phase shift even more important and the phase tuning more difficult. And the last but not least is the interference

with industrial pulse noises which also increases as the resistance of the junction increases. The two former problems could be, in principle, partially solved by lowering the frequency of the modulation but this way would result in the increase of the averaging time of the lock-in amplifier and would also provide the additional problems with the pulse noises as the probability of their appearance during the measurements increases with the duration of the accumulation time, thus making good measurements practically impossible.

That is why we used instead fully DC measurements of the tunnel current and tried to compensate the dynamical range deterioration using proper mathematical treatment of the digital readings.

CIRCUITRY DETAILS

Fig.1 shows a schematic view of the sample under investigations and its equivalent circuit. The latter includes the resistances of the metal leads to the gate and the resistances of the two halves of the δ -layer. The typical values are $C \sim 1$ nF, $R_{Me} \sim 10$ Ohm, $R_\delta \sim 5$ kOhm \div 10 MOhm and $R_{tun} \sim 0.2 \div 300$ MOhm at helium temperatures in the pressure range from zero up to 2 GPa respectively.

Fig.2 shows schematically the circuitry used both to feed the sample with given bias and to obtain the measured current. Its main feature is a usage of Analog Device Ultralow Input Current Operational Amplifier AD549KH with the input bias current lower than 60 fA. The first stage provides the maintenance of the bias voltage applied to the tunnel junction equal to the given output voltage from the DAC, since the voltage drop along the metal leads and along the δ -doped layer is negligible even at δ -layer resistances up to 1 GOhm. The second stage is an ordinary current-to-voltage transformer.

A measurement cycle consisted of the following steps:

1. Performing multiple readings at each given bias voltage.
2. Elimination of the obvious under- and overshoots in the array of these readings with a median filtering and evaluating the dispersion of the rest data set.
3. Using a non-equidistant bias sweep, providing finer steps at biases where *a priori* known features of interest should exist - near zero (for ZBA) and near ± 36.5 mV (for LO-phonon energies).

The measured $I(V)$ curves were subjected to the mathematical treatment to obtain finer features of the tunneling current.

TREATMENT

In a common modulation technique, the compromise between resolution and signal-to-noise ratio is achieved by tuning the amplitude of the modulation voltage.

Our approach includes two-stage smoothing $I(V)$ presented in the tabular form using a smoothing cubic spline. At the first stage the smoothing parameter was chosen so that to obtain the compromise between the noise and the clearness of the many-particle singularities at the second derivative of the spline using weight function inversely proportional to the previously obtained dispersions and "an eye judgement". This procedure is illustrated by Fig.3. At the second stage further smoothing was performed to smooth out the fine features, thus obtaining a background. The latter reveals the energy position of the subbands of the dimensional quantization, and the difference between the first-stage smoothing and the background being the contribution of the many-particle interaction (*cf.* Fig.4). The corresponding fragment of the mathematical routines written in MATLAB are presented in the Appendix A.

CONCLUSION

The comparison of the approaches based on a common modulation technique and the present one shows that the results obtained for the sample eligible for the both of them are consistent with each other. The traditional modulation technique gives about twice better resolution at relatively low impedances, nevertheless fails at highly resistive samples, while the present technique is applicable even for the samples with the resistance in GOhm range.

The present approach has enhanced stability with respect to the industrial noises due to the possibility to eliminate overshoots at the accumulation stage while the traditional one is very vulnerable especially at long accumulation times.

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APPENDIX A

This is a fragment of the simplified MATLAB procedure used to process experimental data.

```

...
% s123 is a three-column array containing bias voltage, current and the dispersion
% Sorting by bias in ascending order
[xx,ii]=sort(s123(:,1));yy=s123(ii,2);ss=s123(ii,3);
% Over- and undershots elimination
mss=mean(ss);ii=find(ss>4*mss);xx(ii)=[];yy(ii)=[];ss(ii)=[];
X=xx/max(abs(xx));Y=yy/max(abs(yy)); %Normalization
% Weights
W0=min(ss+1e-6)./(ss+1e-6)+1;
% The smoothing is less important at biases of interest
%       and more important when obtaining the background.
%       This is accounted for by weights W1 and W2 respectively.
IW=find(xx>-0.045&xx<-0.025|abs(xx)<0.005|xx<0.045&xx>0.025);
W1=W0;W2=W0;W1(IW)=max(W0);W2(IW)= min(W0);
... % Graphic output for the visual audit is skipped
% Build the smoothing cubic spline for I(V)
sp=csaps(X,Y,1-2^(-6),[],W1);
% and calculate the logarithmic derivative of the conductivity
D1=fnval(fnder(sp,1),X); D2=fnval(fnder(sp,2),X); Y1=D2./D1;
% Tabulate on the equidistant grid for convenience
xx2=linspace(xx(1),xx(end),length(xx));
X2=xx2/max(abs(xx2));
Y2=interp1(X,Y1,X2);
% Build the "strongly" smoothing cubic spline for the background
sp2=csaps(X2,Y2,1-2^(-6)/3,[],W2);
% Calculate the background and the many-particle singularities
BG=fnval(sp2,X2); Sings= Y2-BG ;
% The background minima correspond to the subbands position
SubBands=X2(find(diff(sign(diff(BG)))==2)+1);

```

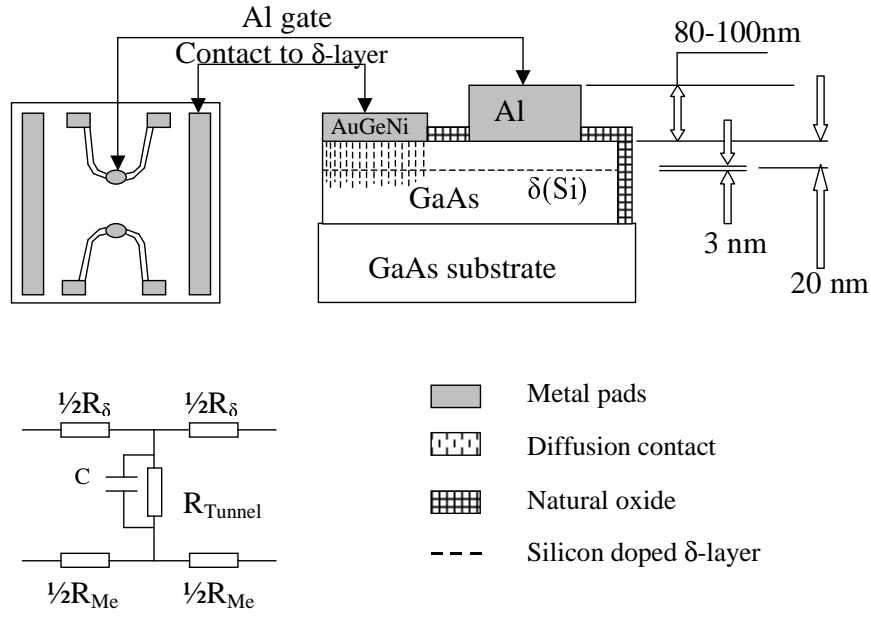


FIG. 1: Plain view, schematic structure and equivalent circuit of the sample Z1B7 [4].

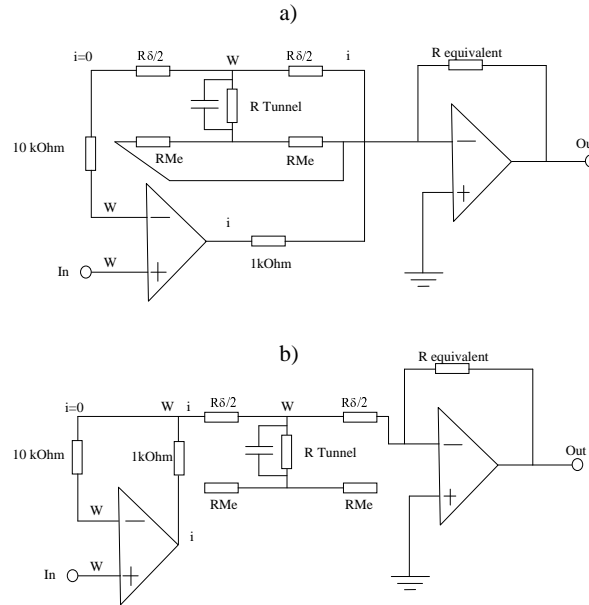


FIG. 2: The principal schematics of the measurement circuit. The controls for initial balancing and commutation are omitted for clarity. a) and b) are the variants for $I(V)$ tunneling and lateral measurements respectively.

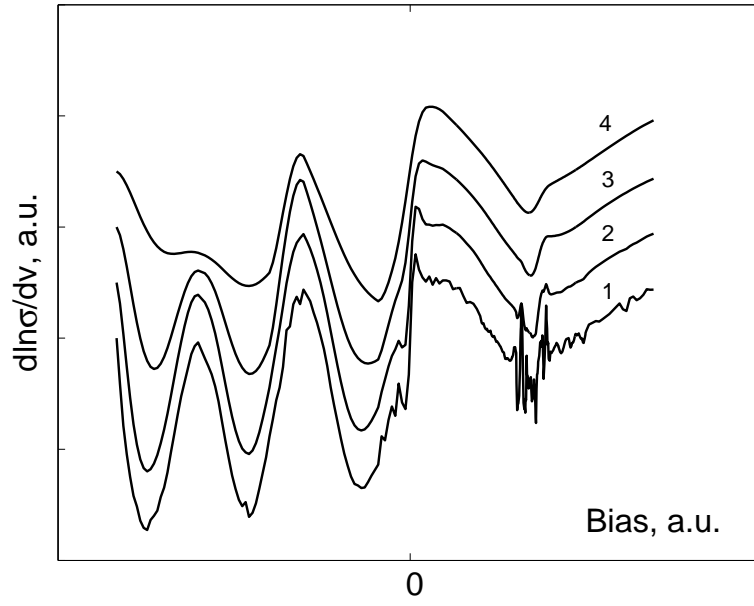


FIG. 3: Shape of the $\frac{d^2I}{dV^2} = \frac{d \ln \sigma}{dV}$ for Z1B7 at zero pressure and at $T = 4.2$ K with different smoothing rates. The curves are enumerated in ascending smoothing rate. The curve 2 is considered to be the best.

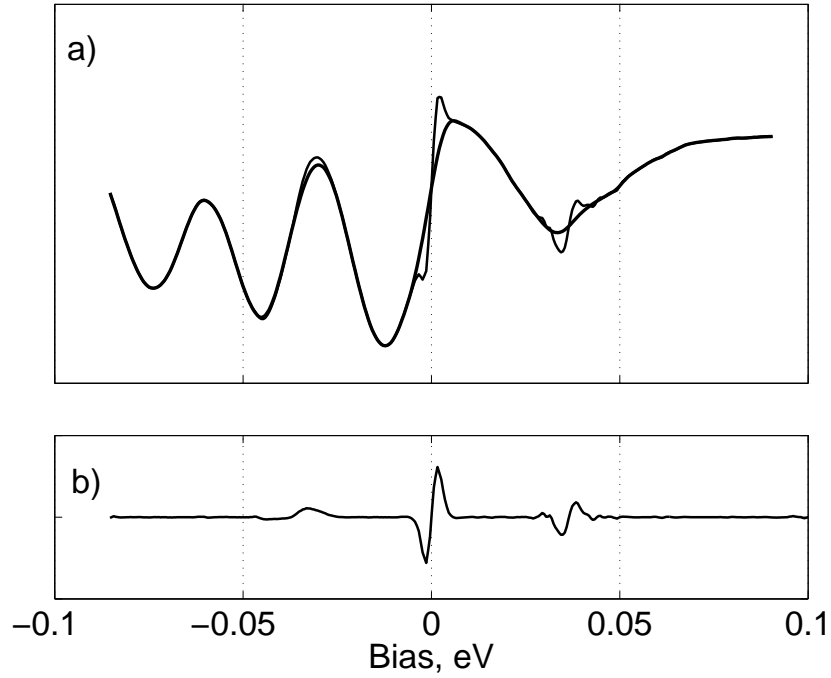


FIG. 4: a) Further smoothing of the curve 2 from Fig.3 results in a background. b) The difference of the above curves gives the contribution due to the many-particle interactions - ZBA and the two LO-phonon structures whose different shapes are physically meaningful.